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Real-Time, Single-Shot, Carrier-Envelope-Phase Measurement of a Multi-Terawatt Laser

D. Adolph,[1,2,*] M. Möller,[1,2] J. Bierbach,[1,2] M. Schwab,[1,2] A. Sävert,[1,2] M. Yeung,[2,3] A. M. Sayler,[1,2] M. Zepf,[1,2,3] M. C. Kaluza,[1,2] and G. G. Paulus[1,2]

[1]Institut für Optik und Quantenelektronik, Abbe Center of Photonics, Friedrich-Schiller-University Jena, Max-Wien-Platz 1,07743 Jena, Germany

[2]Helmholtz-Institute Jena, Fröbelstieg 3, D-07743 Jena, Germany

[3]Centre for Plasma Physics, School of Mathematics and Physics, Queen's University Belfast, BT7 1NN Belfast, UK

We present single-shot carrier-envelope phase (CEP) determination of a 1 Hz, multi-Terawatt (TW) laser system with a setup based on spectral broadening in a hollow-core fiber and a stereographic measurement of the energy-dependent above-threshold ionization (ATI) plateau. The latter, is extremely sensitive to variations in CEP. As compared to f-2f interferometers, this technique reduces the uncertainties due to the shot-to-shot intensity fluctuations, which are prevalent in TW laser systems. The experimental results pave the way towards the investigation and control over CEP-sensitive processes at ultra-high intensities.

Investigation of carrier-envelope phase (CEP) effects in strong-field laser-matter interaction has been a prominent topic of research for more than a decade [1]. The CEP has been shown to be capable of controlling the ionization of atoms [2], the generation of attosecond pulses [3], and the dissociation and ionization dynamics of small [4,5] and more complex molecules [6]. More recently, CEP effects were found to influence strong-field interaction with nanotips [7], clusters [8] and solids [9]. The majority of these investigations have been done at "moderate" intensities between 10^{12} W/cm^2 and few times 10^{15} W/cm^2 using laser systems that typically deliver pulses with up to a few mJ of energy at repetition rates in the kHz range.

Extending CEP measurement and control to the Tera- and Petawatt-class lasers now being built and used in an increasing number of laboratories around the world presents both significant challenges and exciting possibilities. For example, employing loose-focusing geometries has the potential to increase the interaction volume for high-harmonic generation in gaseous media such that attosecond pulses with high pulse energy could be generated from table-top laser systems [10]. Alternatively, tight focusing of these lasers, leads to ultra-high peak intensities far beyond the relativistic limit of 10^{18} W/cm^2 for 800 nm wavelength. In this regime, theoretical investigations of CEP effects have been carried out and predict many interesting effects, e.g., electron bunches generated from laser driven wakefield [11], multiple ionization to high charge states [12] or for relativistically-generated harmonics from plasma targets [13].

Despite the availability of the extremely high intensities and short pulse lengths required to operate in this regime, measurements of the CEP dependence of phenomena here are yet to be realized due to the difficulty in measuring and controlling the CEP. This is because many of the techniques for CEP control of mJ systems are not applicable to Tera- and Petawatt-class systems. For example, to hold the CEP steady, common feedback loops rely upon high repetition rates typically greater than 1 kHz, to feed back information about the system faster than the system is changing. To make such a feedback loop possible, a workaround has been demonstrated [14, 15] by maintaining a kHz pulse train which shares most of the beam path of the amplified low repetition rate TW pulse. However, to make this a viable option the B-Integral in the amplification path, not shared by the kHz pulse train, must be low and should not vary too much from pulse to pulse to keep the CEP jitter low.

In general, implementation of standard feedback techniques for CEP control requires certain performance criteria, which are difficult to achieve for Tera- and Petawatt-class lasers [14, 15]. Therefore, a single-shot CEP measurement of each and every single laser shot in combination with subsequent sorting of the experimental results, i.e. phase tagging, seems to be an ideal way towards the investigation and control of CEP-sensitive interactions in this regime. Phase tagging has already proven to be instrumental for experiments with low-power laser systems, particularly when data acquisition times become longer than the period over which the laser performance can be kept constant [5, 16]. The phase-tagging approach is reminiscent of the procedure in pump-probe experiments involving femtosecond lasers at FELs, where the arrival time delay between X-rays and optical laser is measured for each shot and subsequently the data points are sorted and re-binned with respect to this delay [17, 18]. Further, the added complexity of laser systems in the TW/PW regime, e.g. more

amplification passes and more complex spectral broadening implementations, results in significantly increased shot-to-shot jitter in intensity, pulse duration, and pointing. Thus, a measurement technique that is not strongly skewed by these fluctuations is necessary.

Fig. 1 Experimental setup and typical spectrum after the hollow-core fiber (HCF) with Fourier transform limited pulse. Elements are labeled: (BS) beam splitter, (VW) vacuum window, (AA) apodized aperture, (CEPM) carrier-envelope Phasemeter. The spectral intensity is in black and corresponds to the upper wavelength axis, while the 2.8 fs FTL pulse is in blue and corresponds to the lower time axis.

Here we demonstrate single-shot CEP measurement of the 40-TW JETI laser system at the Institut für Optik und Quantenelektronik in Jena, Germany at 1 Hz repetition rate. This is achieved by measuring the CEP of a few-cycle beam that is coherently derived from the multi-TW laser and regularly used as a probe beam [19, 20]. A tiny fraction of about 1.5 % (12 mJ) of the TW-beam is split off and reduced in diameter by an apodized aperture to 10 mm ($1/e^2$). The transmitted pulses of 1 mJ are spectrally broadened by nonlinear propagation in a Neon-filled hollow-core fiber as shown in Fig 1. The resulting spectrum supports pulses with a Fourier-transform-limited duration of 2.8 fs. After collimation, the spectral phase is compensated using chirped mirrors with a spectral bandwidth ranging from 450 to 1000 nm (UltraFast Innovations) in combination with fused-silica wedges. Finally, the generated few-cycle pulses are steered to the carrier-envelope phase meter (CEPM) [16], using plain silver mirrors.

The CEPM itself has been used in various applications and has been proven to be an effective technique to measure the CEP of kHz laser systems. In addition to measuring the CEP for each individual laser shot, the CEPM has the unique characteristics of being able to simultaneously measure variations in intensity, and pulse length [21]. These are exactly the characteristics needed to deal with the specific properties of extremely intense low repetition rate lasers discussed above. Although the CEPM itself has been described in previous publications [16, 21], it is not as common as standard techniques such as f-2f [22] or f-0f [23] interferometers. Thus, we will briefly describe it, along with its distinct attributes uniquely suited to this application.

The CEPM is based on the spectroscopic measurement of photoelectrons under strong-field conditions. Roughly 50 µJ of pulse energy are used and focused into the Xe gas target inside the CEPM by a spherical mirror with a focal length of 25 cm. The intensity is chosen such that its electric field strength is comparable to the field in the atom. The superposition of both fields creates a potential barrier through which a bound electron can tunnel into a continuum state of the laser field. This sets up conditions for what is commonly known as the three-step model [24, 25], in which an electron is ionized from parent matter, is driven by the electric field away from and then back towards the parent atom where it may recombine and emit high harmonic radiation, double ionize, or elastically scatter off the ion. Those electrons that rescatter off the ion can have energies much greater that those that do not and form a characteristic CEP-dependent feature in the photoelectron spectrum, which is known as the ATI plateau [26]. The ATI plateau has a very pronounced CEP dependence which can be understood already with the three-step model: Photoelectrons in the ATI plateau will only be created if the field strength is large at the instant of initial ionization and during the optical cycle after rescattering. Since both are about one optical cycle apart, fulfilling this requirement depends strongly on the evolution of the pulses' electric field and thus on the CEP [27, 28].

The ATI plateau electrons with an angle of less than ~6° around the polarization axis are detected by two micro-channel plate (MCP) detectors facing one another along the polarization axis at opposite ends, "left" (L) and "right" (R), of a field-free flight tube. For the determination of the CEP, the ATI plateau energy range (~25 to 60 eV) is subdivided into a low- and a high-energy region. The difference of electron yields measured with the two MCPs and normalized to the sum of the yields is defined as the asymmetry, $A = (L-R)/(L+R)$, of electron emission and computed separately for the high- and low-energy region yielding A_{high} and A_{low}. The asymmetry of the electron spectra can be seen in Fig. 2 (b) where the integration regions used are marked. Regarding both as a representation of a laser pulse and using them as Cartesian coordinates yields a parametric asymmetry plot (PAP) (Fig. 2 (a)) in which the angle, ϑ, is used for the CEP measurement. All this can be done with analog electronics [29] to obtain the asymmetries and corresponding ϑ and r values in real-time. For a circular PAP there is a linear relationship between the angle, ϑ, and the CEP where one can estimate the single-shot uncertainty for the CEP determination by dividing the radius by its standard deviation, $\Delta CEP \simeq \Delta\vartheta \simeq r/\Delta r$ [29].

In addition to the CEP, the CEPM also measures the pulse duration and intensity. The radius of the PAP scales inversely with the pulse duration [21] because the magnitude of the asymmetry of the electrical field decreases as the number of optical cycles relevant in the ATI process increases. The scaling of the radius with the pulse duration has been calibrated with a femtosecond SPIDER [21], for pulses with durations in the range between 4 and 9 fs. Note that the precision of the pulse length determination decreases as the radius approaches 1, i.e. as the pulse duration goes below ~4fs. Moreover, for these very short pulses, the PAP can take on a slightly rectangular shape, which leads to r values greater than 1. Therefore, for r values $\gtrsim 1$ the radius of the PAP should be taken as an indication that the pulse is less than 4 fs, but not used as a direct calibration. Additionally, the total yield of electrons increases with intensity. These properties allow the user multiple

options in dealing with the much greater laser fluctuations seen at TW lasers than typical lower-intensity tabletop systems. One can use the information to further differentiate their data, e.g. determine both CEP and pulse-length dependence for a given process with r and ϑ. Alternatively or additionally, bounds can be set on the parameters to exclude data outside the acceptable parameter space, e.g. for intensities or pointing variations too high to yield an acceptable number of electrons.

Fig. 2 (a) Parametric asymmetry plot (PAP) in which the pulse length is encoded in the color of the points. (b) CEP tagged left-right asymmetry of the CEPM. The integration regions that are used to calculate the asymmetry parameters, A_{high} (long dash), A_{low} (short dash) are indicated by dashed lines. (c) Distribution of the pulse duration.

Figure 2(a) shows a distribution of 3500 consecutive laser shots in the PAP. From the measured distribution, a single-shot CEP uncertainty of 160 mrad and mean pulse duration of <4 fs (Fig. 2 (c)), is found for 86 % of all laser shots. The electron yield of the remaining 14 % of the shots was not sufficient to perform an analysis of their asymmetry and could be excluded on the basis previously discussed. The insufficient electron yield is likely due to laser instabilities in energy, which was within 3 % rms, and pointing fluctuations of the TW laser, which cause strong deviations in energy and spectral broadening at the output of the HCF. Also, for the 86 % of shots used, these effects increase the spread in the radial coordinate, i.e. in the pulse duration of the few-cycle probe. Due to the fact that the mean pulse duration is less than 4 fs, this spread does not significantly reduce the precision of the CEP measurement.

As an example, we recorded the left and right energy-dependent ATI spectra from the CEPM for each laser shot and tag the data with its CEP. Note that in general the full spectra do not need to be recorded as the analog electronics can determine the asymmetry parameters and CEP in real time. From these spectra, the time-of-flight-resolved asymmetries are calculated and shown in Fig. 2 (b) along with the used integration regions. For the investigation of unknown CEP-dependences in, e.g. relativistic laser plasma dynamics, the process under consideration would be measured using the primary high-intensity beam and tagged with the CEP, and optionally intensity and pulse duration information, from the CEPM. Note that this allows for the determination of the relative CEP-dependence as there is a fixed offset between the CEP of the TW beam in the interaction region and that measured in the CEPM, φ_0. If absolute CEP-dependence is required, then one can use a process with a well-known absolute CEP-dependence to determine and account for this offset [30]. Furthermore it must be pointed out that tagging of the pulse duration is only meaningful if the pulse duration of the laser system is short enough, <12fs, to be able to omit the hollow core fiber.

It is known that pointing and pulse-energy fluctuations at the input of a hollow-fiber compression setup change the CEP of the compressed few-cycle pulse [31]. Thus, the offset, φ_0 is dependent on the input pulse energy and the pointing stability of the multi-TW laser, which in turn adds uncertainty to the shot-to-shot CEP measurement. Considering typical energy stabilities of state-of-the-art TW- laser systems of 1 % and better, one can roughly estimate that an uncertainty of ~130 mrad [31] must be added to the uncertainty of the CEPM due to the intensity-CEP coupling in the HCF. Larger or additional fluctuations will naturally increase this uncertainty. However, as already discussed, the additional information provided by the CEPM can be used to mitigate the problems. This precision compares well to typical values at kHz systems where CEP tagging is regularly done, which indicates that the setup presented here will allow for CEP-dependent measurements with Tera- and Petawatt lasers.

Although recent publications have demonstrated CEP-stabilized 10 Hz TW laser systems where f-to-2f interferometers were used to measure and stabilize the CEP [14, 15], this technique has significant trade-offs compared to the technique presented here. Namely, f-2f interferometers can operate with much longer pulses and the commercial availability makes for easier implementation. However, f-2f interferometers are much more, approximately a factor of 3 times more [29], sensitive to intensity fluctuations and do not provide pulse length and intensity information. Since shot-to-shot intensity fluctuations are one of the most difficult properties of TW systems to control, the relative insensitivity to and measurement of the intensity fluctuations by the CEPM implementation is a significant advantage. As compared to standard f-2f schemes [32], the setup presented here is simple to align, works with relatively poor shot-to-shot stability and is easy to use even at low repetition rates.

In summary, a technique for CEP tagging of a multi-TW laser beam using a CEPM is proposed, implemented, and tested. The setup employs hollow-core fiber compression of a small fraction of the TW beam to generate few-cycle pulses, which are used to determine the CEP and pulse duration of these few-cycle pulses using the CEPM. Due to the unique properties of the CEPM, including its relative insensitivity of the phase measurement to intensity fluctuations along with simultaneous measurement of intensity and pulse length fluctuations, it is an ideal technique to investigate CEP dependent processes at Tera- and Petawatt-class lasers with low repetition rate.

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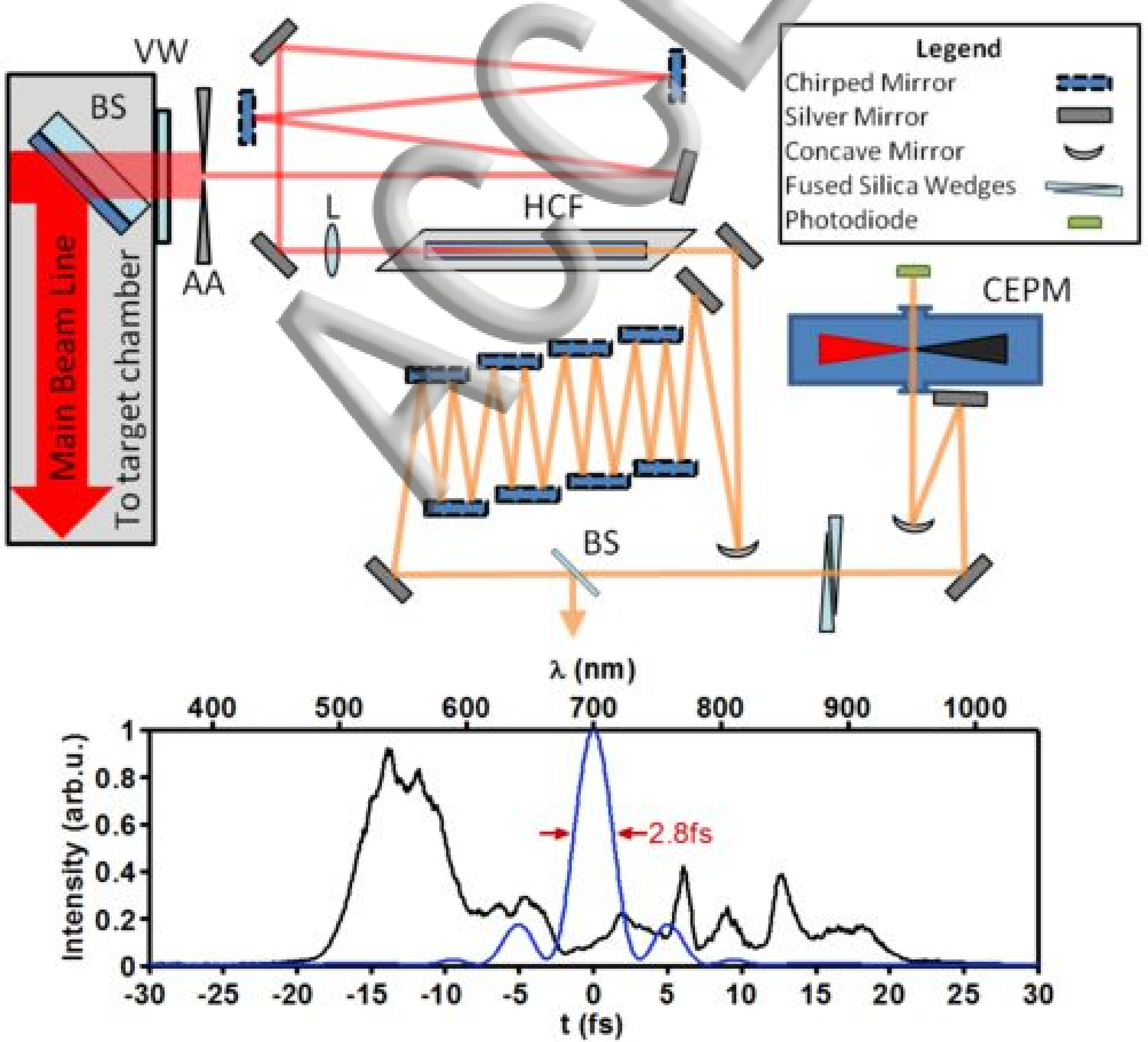
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AA
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HCF
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To target chamber
Legend
Chirped Mirror
Silver Mirror
Concave Mirror
Fused Silica Wedges
Photodiode
CEPM
BS
λ (nm)
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500
600
700
800
900
1000
Intensity (arb.u.)
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0.6
0.4
0.2
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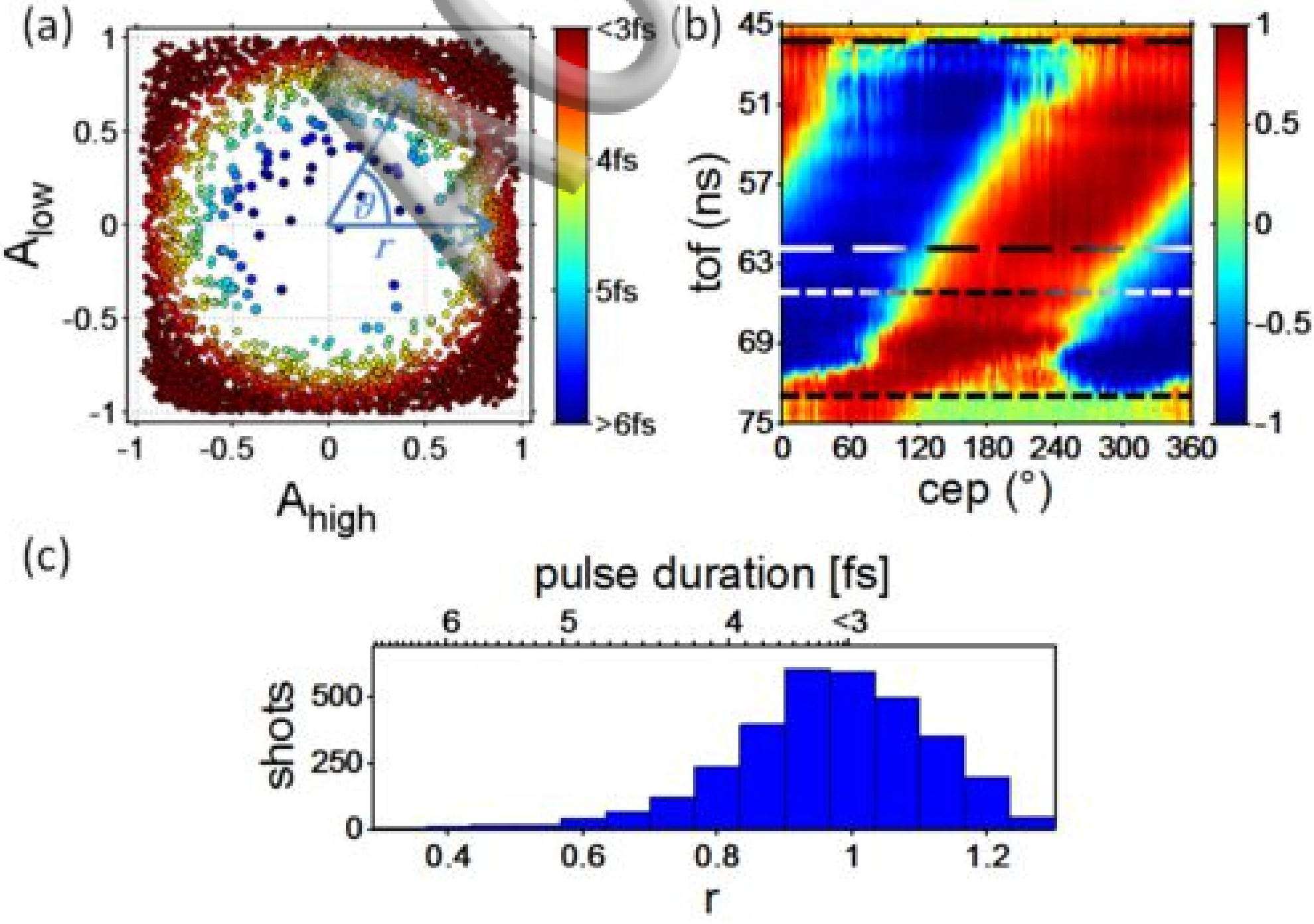
(a)
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